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Hotspots of peatland-derived potable water use identified by global analysis

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Abstract:

Peatlands cover approximately 2.84% of the Earth's land surface and store around 10% of all non-glacial freshwater. However, the contribution of peatlands to global potable water resources is unclear since most peatlands are remote from major population centres, and until now no systematic, global assessment of peatland water resources has been undertaken. Here we analyse global peatland, population and hydrometric datasets to identify hotspots where peatlands are crucial for water supply, and show that these peat-rich catchments deliver water to 71.4 million people. Water supply peatlands cover just 0.0015% of the global land surface, yet provide 3.83% of all potable water stored in reservoirs. Approximately 85% of all drinking water delivered directly from peatlands is consumed in the UK and the Republic of Ireland, meaning that peatlands play crucial roles in the water security of these nations. Globally, only 28% of water-supply peatlands are pristine or protected, highlighting the urgent need for responsible stewardship. Our findings provide global evidence for the often assumed role of peatlands in sustainable water resource provision and for informing peatland water-resource protection policies.

Introduction

Peatlands cover around 4.23 million km^2 and represent at least a third of global wetland habitat[1,2]. A tenth of the world's non-glacial freshwater is thought to be held in peatlands[3], although this estimate is highly uncertain, and it is unclear how much of this water is readily available as a resource. Nonetheless, water provision is a commonly stated ecosystem service of peatlands. High dissolved organic carbon (DOC) concentrations means that water draining from peatlands usually requires treatment before it can be used for drinking water. Other than DOC, water draining from pristine peatlands is often of good quality, meaning that these landscapes are potentially important to sustainable provision of potable water[4-6].

Peatland degradation is thought to be accelerating in temperate[7,8], tropical[9,10] and boreal[11,12] environments due to rising temperatures and enhanced frequency and severity of droughts. Projected climate change to 2100 is predicted to cause severe degradation of some peatlands[13], resulting in accelerated peat decomposition, release of aquatic carbon and reduction in peatland water quality[7]. In addition, rising temperatures and changing precipitation regimes are likely to increase fire risk in many peatlands[14-16], which further threatens their sustainable provision of water resources. Peatlands are also under threat from exploitation for fuel, timber and drainage for arable land[17-19], including palm-oil plantations in Southeast Asia[20]. Peatlands close to human populations are at greater risk of exploitation and degradation, but are also likely to play a more important role in water resource provision. There is evidence that artificial drainage, which has impacted approximately 12% of global peatland area[17], has led to poorer water quality and enhanced fluvial organic carbon fluxes[21-23]. This degradation of water quality will increase costs of water treatment, because the by-products of disinfecting organic-rich waters often contain potential carcinogens which are strictly regulated in many countries[24-26].

Although peatlands are potentially important water sources for humans, the world's largest peat complexes (e.g., the Western Siberian Lowlands and the Hudson Bay Lowlands) are remote from major population centres and therefore seem unlikely to play as valuable a role in water resource provision as their large area and high water storage capacity might at first suggest. Little is known about the role of peatlands in providing potable water resources at either global or regional scales. A global synthesis has the potential to identify where human populations are most dependent on peatlands for their water supply services, and where enhanced public and policy attention should therefore be directed towards peatland conservation and stewardship in order to sustain water security in the face of changing climate and land use.

We developed the Peat Population Index (PPI) to quantify objectively the global coincidence of human population and peatland cover at catchment scales. In PPI hotspots we investigated in closer detail the contribution of peat-derived water to potable water resources abstracted from both reservoirs and river. We developed another global index, the Peat Reservoir Index (PRI), which quantifies the catchment-scale contribution of peatlands to potable water abstraction from reservoirs. We used these indices to estimate the quantity of global potable water that has drained from or through peatlands (see Methods). We also investigated the degree of degradation in these water supply peatlands. Our findings provide the first global evidence base for establishing the role of peatlands in providing water security, and can be used to inform peatland protection policies in water supply zones.

Basin scale coincidence of peatland cover and humans

The Peat Population Index (PPI) represents the proportion of peatland cover (Supplementary Figure 1) in a catchment multiplied by the catchment's population density (Supplementary Figure 2). PPI represents the coincidence of people and peatlands at the catchment scale and identifies locations where a large population may rely heavily on peatlands for ecosystem services such as potable water supply (Figure 1). We used global datasets of peatland cover, population, hydrography, digital elevation, and land-use to calculate proportion of peatland cover and population density in each catchment around the world, from which we calculated PPI for each catchment.

Figure 1. Global PPI distribution at the catchment scale, calculated based on the proportion of peatland multiplied by the population density for each catchment. a. PPI hotspot in south-eastern United States, b. PPI hotspots in Western Europe.

Use of the Jenks optimisation classification[27] (see Methods) resulted in eight hotspot catchments being identified where PPI is at least 106 persons km^{-2}, indicating populace catchments with high peatland cover.

Seven of the eight PPI hotspots are in Western Europe, and the other is in the Florida Everglades. Detailed analysis of river and reservoir water abstraction data (Supplementary Text) reveals that potable water resources in PPI hotspot catchments in the Netherlands and the Everglades are mainly groundwater fed, with relatively little direct supply from peatlands (less than 0.1%). However, in PPI hotspots in the UK and the Republic of Ireland, peatlands play important roles in providing potable water to large conurbations (Table 1). The peatlands responsible for supplying these high volumes of potable water in the UK and Ireland are all situated in upland areas (at least 300 m above sea level). Lowland peatlands in PPI hotspot catchments generally made little contribution to potable water provision, although such peatlands are often drained for agricultural uses, such as in the lowland East Anglian Fens, UK[28].

Since PPI represents the product of peatland cover and population density in a catchment, its value in sparsely-populated but peat-rich catchments is usually low despite extensive peatland cover. For example, the Scandinavian catchment with the largest PPI value is the Glomma catchment in Norway, but the PPI is only 7 persons km^{-2}. Even though this catchment contains 2840 km^2 of peatland, equivalent to a tenth of catchment's total area, population density is only 72 persons km^{-2}. Similarly, the largest PPI value in West Siberian catchments is only 5 persons km^{-2} and the PPI values of all catchments in the Hudson Bay Lowlands are less than 1 person km^{-2}.

Table 1 The characters and potable water provision by peatlands in the eight PPI hotspots catchments

Catchment	Catchment area (km^2)	Largest Conurbations	Peatland percentage (%)	Population density (persons km^{-2})	PPI (persons km^{-2})	Directly-sourced peat-derived water use (million litres day^{-1})	Population using directly-sourced peat-derived water (million persons)	Country	Peatland topographic situation	Do peatlands play a significant role in potable water provision?
Ribble	2958	Preston	11.9	918	109	78.88	0.52	United Kingdom	Upland	Yes
Aire-Calder	2514	Leeds	7.8	1354	106	25.34	0.17			
Liffey	3203	Dublin	17.8	677	120	153.99	1.25	Republic of Ireland		
Nieuwe Maas	614.	The Hague	6.7	2686	180	0.94	0.01	Netherlands	Lowland	No
Oude Rijn	1083	Utrecht	30.2	1350	407					
Nederrijn	2639.	Rotterdam	12.4	958	118					
Zuiderzee	5136.	Amsterdam	13.5	1025	137					
Everglades	20630	Miami	37.9	386	146	<0.01	<0.01	United States		

Global contribution of peatlands to potable water

Peat-fed water supply systems include reservoirs and rivers from which potable water is abstracted, and in which flow accumulation upstream of the abstraction point includes peatland cover. Peatlands are rarely the only sources of water in water supply systems, which are usually also fed by portions of the landscape without peat cover. We distinguish between water that has flowed directly through or across peat prior to entering a potable water supply (henceforth, directly-sourced peat-fed water); and the larger volume in a water body that includes a mixture of peat-fed water and water that has not come into contact with peatlands (mixed-source peat-fed water). We estimate the total storage capacity of peat-fed water supply reservoirs globally to be 4.35 km^3, and that they deliver approximately 3.67 km^3 $year^{-1}$ of mixed-source peat-fed potable water, equivalent to supporting a population of 63.5 million people on a per capita basis (Supplementary Table 1). Regions with the most extensive peat cover (e.g. Western Siberian Lowlands, Hudson Bay Lowlands; and parts of Scandinavia, Alaska, and Amazonia) are remote from large conurbations and have barely any connection to water supply reservoirs or stream abstraction points. We identify 56 peat-fed water supply reservoirs in 34 different catchments; 27 of these catchments are in Europe, three in North America, two in Australia, and one each in Asia and South America. Europe holds 47 of the 56 peat-fed water supply reservoirs (Supplementary Table 1).

We developed the Peat Reservoir Index (PRI) to quantify the direct contribution of peatlands to water supply reservoirs on a catchment basis. PRI is defined as the volume of directly-sourced peat-fed water from reservoirs, and complements our use of PPI. For each catchment, the PRI is calculated from the annual volume of domestic water supplied by reservoirs multiplied by the proportion of streams that have interacted with peatlands before draining into those reservoirs (see Methods). The global distribution of PRI is shown in Figure 2 and Supplementary Table 1. Globally, we estimate that PRI to be 0.76 km^3 $year^{-1}$, meaning that approximately 20.09 % of mixed-source peat-fed potable water from reservoirs is directly sourced from peatlands, equivalent to supporting a population of 13.47 million people on a per capita basis. At the continental scale, abstraction of directly-sourced peat-fed drinking water from reservoirs (PRI) is most important in Europe (689.27 million m^3 $year^{-1}$), followed by North America (44.20 million m^3 $year^{-1}$), South America (23.50 million m^3 $year^{-1}$), Asia (2.04 million m^3 $year^{-1}$) and Oceania (0.21 million m^3 $year^{-1}$).

Figure 2 Global PRI distribution at the catchment scale. 2a the UK and Republic of Ireland, 2b Germany, Belgium and the Czech Republic, 2c China, 2d Brazil, 2e United States and Canada, 2f Oceania (black numbers represent the PRI values).

Water supply networks commonly transcend topographic catchment boundaries, with drinking water abstracted from reservoirs and distributed to large conurbations in neighbouring catchments. This means that peat-sourced water may still be important in urban catchments where peat cover is low (and which are therefore not identified by PPI) if a sizeable fraction of drinking water is extracted and pumped from neighbouring peat-rich catchments, such as from reservoirs in rural areas. For example, Thirlmere reservoir in the Lake District National Park, England, supplies approximately 226.5 million litres of water per day, while the nearby Haweswater reservoir supplies a further 121.4 million litres of water per day, to settlements in north-west England beyond the boundaries of their own catchments, including Greater Manchester (see Supplementary Table 1). Therefore, a coincidence of high PPI and high PRI may occur in some catchments (e.g. River Liffey catchment, Republic of Ireland), but not all. Most high PRI catchments are in close proximity to high PPI catchments, even if they are not coincident (Figure 3).

Figure 3 Distribution of PPI hotspot catchments and their nearby high PRI catchments in the UK and Republic of Ireland (black numbers represent the values of PRI).

High PPI catchments with peatlands in headwater locations indicate where people are most likely to rely heavily on peatlands to provide potable water resources. The 46 catchments with the highest PPI (the top three PPI categories based on Jenks optimisation classification, with PPI values of at least 36 persons km^{-2}) contain 1,482 km^2 of upland peatland cover. 1302 km^2 (87.9%) of these upland water-supply peatlands are concentrated in just five UK and Irish catchments, three of which are identified by our analysis as PPI hotspots and which we have analysed in closer detail (see Supplementary Text); the remaining two are PRI catchments that neighbour PPI hotspot catchments. We suggest that mixed- and directly-sourced peat-fed water consumption in PPI hotspots, added to that supplied from neighbouring PRI catchments, provides a representative estimate of the vast majority of global potable water derived from peatlands.

We estimate the total peatland area that contributes potable water to reservoirs in PRI catchments and to stream abstraction in PPI hotspots (hereinafter referred to collectively as water supply peatlands) to be 2314 km^2, equivalent to just 0.05 % of global peatland area or 0.0015 % of the global land surface area. However, approximately 3.83 % of potable water stored in reservoirs globally is mixed-source peat-fed water. Water supply peatlands provide approximately 4.22 km^3 yr^{-1} of mixed-source peat-fed potable water globally, which is consumed by 71.4 million people. Approximately 0.80 km^3 yr^{-1} of this is directly-sourced peat-fed potable water, equivalent to supporting a population of 14.27 million people on a per capita basis. The global PRI value of 0.76 km^3 yr^{-1} means that more than 93% of all directly-sourced peat-fed potable water is reservoir derived. Water-supply peatlands are concentrated in north-western Europe; the vast majority of these are located in catchment headwaters, where they have the potential to exert a strong biogeochemical influence on downstream waters. The UK in particular is heavily reliant on peat-fed reservoirs for potable water provision. UK water-supply reservoirs have a total storage capacity of 1.82 km^3, of which 1.32 km^3 (72.5 %) is peat-fed.

Our global analysis identifies that use of potable water delivered by peatlands is highly concentrated in important hotspots. The annual volume of mixed-source peat-fed potable water is particularly high in the UK and the Republic of Ireland, estimated at approximately 1.75 km^3 yr^{-1}. These two nations consume approximately 0.68 km^3 yr^{-1} of directly-sourced peat-fed potable water, equivalent to 85 % of the global consumption of directly-sourced peat-fed water. Peatlands cover 9.12 % of the UK[1], although water supply peatlands cover only 0.31 %. Nonetheless, the UK consumes approximately 1.56 km^3 yr^{-1} of mixed-source peat-fed potable water, equivalent to supporting 28.25 million people or 43.1 % of UK population. Out of this potable water volume, 0.63 km^3 yr^{-1} is directly-sourced from peatlands. The Republic of Ireland consumes 0.19 km^3 yr^{-1} of mixed-source peat-fed potable water, equivalent to supporting 4.22 million people or 68% of the national population. In contrast, the world's largest peatland complexes such as those in Alaska, Western Siberia, the Hudson Bay Lowlands, Scandinavia, and the Amazon and Congo basins are largely unimportant to provision of human drinking water, although they represent huge carbon stores[29,30]

Sustainable water supply from modified peatlands

Peatlands are potentially sensitive to land-use change[19,31], and once degradation is initiated these systems can rapidly denude and degrade[32]. We used land-use as an indicator of degradation in water supply peatlands around the world by interrogating the Ecosystem-Land Use System[33] (see methods). We estimate that only 651.7 km^2, or 28.17 %, of water supply peatlands globally were pristine or protected as of 2010 (Table 2), determined from the Global Ecosystem-Land Use System[33]. Anthropogenic pressures on peatlands may therefore threaten their water supply function[34]. The most common land-use activity on water-supply peatlands is arable and livestock hill farming, particularly in the UK. Overgrazing often leads to peatland erosion and degradation[35,36], while arable cropping on peatlands has resulted in peat mass loss[37,38] and nutrient loading of water courses[39,40]. Both activities have been shown to increase fluvial aquatic carbon loss from peatlands which will enhance water treatment costs downstream[41]. Upland peatlands in the UK play an important role in potable water provision, and are uniquely and severely degraded in a global context[32]. In England, up to 96% of deep peatlands, most of which are located in upland headwaters, are subject to degrading land-management practices and historic pollution[42]. Concentrations of DOC in water from UK upland peatlands have increased rapidly in recent decades due to a combination of changes in atmospheric deposition chemistry and peat degradation[43]. Changes in future climate also further threaten the stability of these peatlands and water treatment costs[31,44]. Removal of peat-laden sediment and DOC from water draining from degraded peatlands represent the largest costs in raw water treatment for water utilities in the UK[45]. For example, in Bamford Catchment, a 200 km^2 upland water supply catchment in Derbyshire, England, Severn Trent Water spend at least $200,000 per year on removing sediment from raw water to meet drinking water standards (data courtesy of Severn Trent Water). The costs of dealing with further degradation from land management[24,25] or climate change[13] could be substantial as capital investment in new treatment works are required to cope with water from more degraded peatlands. Such investment can amount to as much as $1 million and $3 million per thousand people[46,47]), and is compounded by enhanced energy and chemical treatment costs each year. Restoration and protection of potable water supply peatlands in order to improve water quality[48,49] may therefore deliver enhanced sustainability of water supply as well as a reduced cost burden on society[50].

Table 2 Land use on global potable water supply peatlands in 2010

General land use	Specific land use	Peat area (km^2)	Percentage of peat (%)
Pristine or protected	Forest - protected	129.35	5.59
	Grasslands - unmanaged	0.07	0.00
	Grasslands - protected	64.90	2.81
	Shrubs - unmanaged	46.30	2.00
	Shrubs - protected	318.21	13.75
	Agriculture - protected	72.70	3.14
	Sparsely vegetated areas - protected	0.80	0.03

	Open Water - unmanaged	3.23	0.14
	Open Water - protected	16.15	0.70
	Total	**651.70**	**28.17**
Low-intensity agricultural activities	Shrubs - low livestock density	0.02	0.00
Moderate- and high-intensity agricultural activities	Forest - with agricultural activities	34.70	1.50
	Forest - with moderate or higher livestock density	109.34	4.73
	Grasslands - moderate livestock density	23.18	1.00
	Grasslands - high livestock density	152.48	6.59
	Shrubs - moderate livestock density	3.80	0.16
	Shrubs - high livestock density	80.46	3.48
	Rain-fed crops (subsistence/commercial)	4.31	0.19
	Crops and moderate intensive livestock density	675.29	29.19
	Crops and high livestock density	114.24	4.94
	Open water - inland fisheries	12.43	0.54
	Total	**1210.23**	**52.31**
Settlement	Settlement land	451.65	19.52
Global potable water supply peatlands		**2313.60**	**100.00**

It should be noted that our estimate of the global volume of potable water supplied by peatlands is a conservative one, since it only considers 87.9 % of upland peatlands in the 46 catchments with the greatest PPI. Our global PRI value is also a conservative estimate. The GRanD database used to generate the index includes all reservoirs with a storage capacity of at least 0.1 km^3 and another 3988 smaller reservoirs (<0.1 km^3) for which data are available[51]. However, there are numerous additional small reservoirs with a storage capacity less than 0.1 km^3 which are excluded from the database and therefore from our analysis. Reservoirs for which domestic water supply is a secondary use (e.g. those mainly used for producing hydroelectricity) are also excluded (see Methods) and therefore represent a further small source of underestimation. Ongoing efforts to develop high resolution, gridded maps of population, topography, surface hydrology, peatland cover and land-use will allow future refinements of our estimates of potable water provision from peatlands. However, our estimate is based on the best available data at the time of writing and represents the first global inventory of peatland water resources, which might improve the evidence base on the management of peatlands to achieve the UN's Sustainable Development Goals for 'Clean Drinking Water' and 'Life on Land'.

Methods

Peatland spatial data

We used a recently-published global peatland map[1] as our source data for peatland extent. PEATMAP contains spatial data on peatlands that are of direct relevance to peatland extents, possess a fine spatial resolution, and are up to date.

Population database

Global population distribution information was derived from the Gridded Population of the World (GPW V4) database (CIESIN, http://dx.doi.org/10.7927/H4D50JX4). GPW V4 is a 30 arc-seconds (c. 1 km at the equator) dataset which contains global population counts, density, urban/rural status, age and gender structures with more than 12,500,000 input units maintained by NASA's Socio Economic Data and Applications Center (SEDAC). For GPW V4, population input data are collected at the highest resolution available from the results of the '2010 round' of censuses, which occurred between 2005 and 2014. Most sources for GPW V4 were national statistical collected data in 2010.

Hydrography dataset

The 15 arc-second digital elevation model (DEM), river network, drainage direction and flow accumulation (FAM) data provided by Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS)[52] were used along with the sub-basin catchment boundary datasets provided by AQUASTAT (http://www.fao.org/nr/water/aquastat/maps/index.stm). HydroSHEDS is a gridded global dataset providing information in a consistent and format for regional and global scale applications[52]. The flow accumulation (FAM) derived from HydroSHEDS defines the accumulated hydrologic flow values (weight of all cells flowing) into each downslope cell in the output raster, and the outlets of the streams, rivers, or drainage areas have the largest values.

The AQUASTAT dataset delineates major catchment boundaries and sub-basin catchment boundaries based on the HydroSHEDS dataset (e.g. drainage direction, flow accumulation) while the constituent rivers of these catchments (e.g. the Strahler stream order level, river network, catchment names) were derived from the FAO hydrological metadata. To extract more comprehensive information, the 15 arc-seconds (c. 500 m at the equator) sub-basin boundaries were used rather than major catchment boundaries from AQUASTAT. The sub-basin boundaries of AQUASTAT were based on the HydroSHEDS dataset and delineated based on the Strahler stream order level from FAO hydrological metadata which offers the possibility to split sub-basins at any confluence where the inflowing branches (i.e. a tributary and its main stem) exceed a certain stream order level threshold - level three. Due to catchment boundaries in Siberia being incomplete in AQUASTAT, we used the HydroBasins level five resolution sub-basin boundary for Siberia[53]. The level five sub-basin boundary is the closest to that used in AQUASTAT for other regions of the world. It should be noted that this would little affect the calculations of peatland potable water provision for human use, since the population of Siberia is extremely sparse.

Global Reservoir and Dam (GRanD) database

The Global Reservoir and Dam database (GRanD)[51] developed by Global Water System Project (GWSP) contains 6862 records of reservoirs with a cumulative storage capacity of 6,197 km^3. The GranD includes all reservoirs with a storage capacity of more than 0.1 km^3 and 3988 smaller reservoirs (<0.1 km^3) for which data are available. The associated reservoir dataset includes attributes that we used in our studies such as the name of the dam and impounded river, primary or secondary use and the storage capacity of the reservoir.

Calculation of Peat Population Index (PPI)

The Peat Population Index (PPI) was developed to quantitatively describe the coincidence of humans and peatland cover in a catchment. The PPI represents how many people are associated with peatlands in per km^2 of a catchment. This is useful from an ecosystem services perspective as it provides information showing those catchments where a lot of people will be rely heavily on peatlands for a variety of services. For each catchment, PPI was calculated by:

$$PPI_i = DPOP_i \times PPEAT_i = \frac{\sum_{j=1}^{n} APOP_j}{A_i} \times \frac{APEAT_i}{A_i} \quad (1)$$

where PPI_i is the value of Peat Population Index in catchment i (persons km^{-2}), in PPI, the km^{-2} is the unit of catchment area rather than of peatland area, $PPEAT_i$ is the proportion of peatland in a catchment i (range from 0-1), and $DPOP_i$ is the population density of a catchment i (persons km^{-2}).

The processing steps to combine each dataset and estimate the value of PPI in each catchment were as follows:

Calculation of peatland area in each catchment

To calculate the area of peatland in each catchment, individual peatlands were identified and ascribed to catchments, by using the 'Identity' tool in ArcGIS 10.4[54]. The peatland area in each catchment was calculated by:

$$APEAT_i = \sum_{j=1}^{n} APEAT_j \quad (2)$$

where $APEAT_i$ is the area of peatlands in catchment i (km^2), n is the number of peatland polygons in catchment i, i is the code of the catchment. Based on the peatland area and catchment area, we calculated the percentage of peatland cover for each catchment:

$$PPEAT_i = \frac{APEAT_i}{A_i} \quad (3)$$

where $PPEAT_i$ is the percentage of peatlands in catchment i, A_i is the area of catchment i (km^2).

The global peatland abundance as a percentage of each catchment is shown as Supplementary Fig. 1.

Calculating total population in each catchment

The global population density dataset has more than 12.5 million input units which need to be allocated to pixels in each catchment. The 'Zonal Statistics' tool in ArcGIS 10.4 was used to calculate the population density raster within catchments. The population total and density of each catchment were calculated by:

$$APOP_i = \sum_{j=1}^{n} APOP_j \tag{4}$$

where $APOP_i$ is the gross of population in catchment i (km^2), n is the number of population density points in catchment i, i is the code of the catchment and

$$DPOP_i = \frac{\sum_{j=1}^{n} APOP_j}{A_i} \tag{5}$$

where $DPOP_i$ is the population density in catchment i, and A_i is the area of catchment i (km^2).

The population density distribution at the catchment scale is shown as Supplementary Fig. 2.

Calculation of the Peat Reservoir Index (PRI)

Normally peatlands are not the only water sources for a peat-fed reservoir, as reservoirs could be fed by rivers drained from other non-peatland water sources. Therefore, the proportion of stream flow that interacted with potable water supply peatlands before draining into reservoirs should be considered in order to estimate the volume of potable reservoir water directly supplied by peatlands. Here, we develop the Peat Reservoir Index (PRI) to describe the contribution of peatlands to water supply reservoirs in a catchment, and it indicates the volume of potable reservoir water directly supplied by peatlands (directly-sourced peat-fed potable water). For each catchment, PRI can be calculated by:

$$PRI = \sum_{i=1}^{n} V_{Reservoir(i)} \times P_{Stream(i)} \tag{6}$$

where PRI is the Peat Reservoir Index (million cubic meters per year) in a catchment, $V_{Reservoir(i)}$ is the volume of annual potable water supplied by peat-fed water supply reservoir

i (mixed-source peat-fed potable water) (million cubic meters per year), $P_{Stream(i)}$ is the proportion of stream flows that have interacted with peatlands before draining into reservoir i (range from 0-1), and n is the number of peat-fed water supply reservoirs in a catchment.

The processing steps to combine each dataset and estimate the value of PRI in each catchment were as follows.

Identifying potable water supply peatlands

Peatlands not only provide raw water directly for human use but can also alter the quality of the flowing water. Therefore, those peatlands which have interacted with streams before draining into potable water sources (including headwater and riparian peatlands) can be defined as 'potable water supply peatlands'. The potable water supply peatlands were identified by overlaying PEATMAP[1] with the river networks of potable water sources and flow direction data.

Identifying peat-fed water supply reservoirs

Identify the potable water supply reservoirs

The GRanD database provides information on the main utility and secondary utility of reservoirs. These reservoirs can be classified into those mainly used for water supply, or those with a different primary purpose (i.e. irrigation, hydroelectricity production, flood control, recreation, navigation, fisheries, pollution control, livestock water supply) but with a secondary use for water supply. When the water supply was the secondary utility of reservoirs, except in the case of recreation, most of the storage capacity of reservoirs is used for irrigation, hydropower, flood control or navigation rather than providing potable water. Hence the potable water supply function of reservoirs will be overestimated if we included those. In contrast, many water supply reservoirs are open to the public for recreation, and the utility of recreation does not affect the volume of annual potable water supply. Therefore, in order to avoid overestimation, this study only used reservoirs which are mainly used for water supply, or primarily used for recreation and had a listed secondary use of water supply.

Determine the peat-fed water supply reservoirs

Peat-fed water supply reservoirs refer to those water supply reservoirs for which the impounded streams have interacted with peatlands before draining into the reservoirs. These reservoirs were determined by combining data on water supply reservoirs, PEATMAP and river network systems. As some of the source data of the GRanD database are outdated, some reservoirs in the list may no longer be used for drinking water supply (e.g. Bukowka reservoir in Poland; Vojmsjön in Sweden). In addition, the database cannot distinguish between industrial water supply reservoirs and potable water supply reservoirs (e.g. Spremberg and Pöhl reservoirs, Germany). Therefore, we checked and then removed 13 reservoirs from the peat-fed potable water supply reservoir list. In addition, there are 1577 reservoirs in the GRanD database which have no data about their utility. To avoid omitting potential peat-fed water supply reservoirs, the main utility of these reservoirs was determined from the literature, where these reservoirs also occurred in systems with peat present. In total, this added two more reservoirs to the peat-fed potable water supply reservoir list (i.e. Wanjiazhai reservoir in China and Upper Mangatawhiri reservoir in New Zealand). At the same time, to avoid underestimation, we checked peat-fed reservoirs that are mainly used for irrigation, hydropower, flood control or navigation and had a listed secondary use for water supply to determine if they have recently changed to mainly supply potable water. In total, this added three more reservoirs to the peat-fed potable water supply reservoir list (Poulaphuca reservoir and Vartry Reservoir in the Republic of Ireland and Colby Lake reservoir in the United States). Overall, we found 56 peat-fed water supply reservoirs in total 859 water supply reservoirs in GRanD. However, the water supply volume of the reservoirs is not provided by GRanD, so here we extracted data from literature (i.e. statistics, dam plans literature, water company reports, or abstraction licences) to extrapolate the volume of annual water supply from all of these peat-fed water supply reservoirs (see Supplementary Table 1).

Interaction of reservoir input streams and peatlands

Identify the outlets of potable water supply peatlands

Flow accumulation maps display values that represent the number of input cells which contribute water to any other given cell; the outlets of streams or rivers will typically have the largest values. Potable water supply outlets include outlets of rivers draining from (through) peatlands and the river or reservoir abstraction points. If a stream originated from peatlands and flowed through other peatlands within the same catchment, then we only identified the cell with the largest value of flow accumulation as the peat potable water supply outlet in order to avoid repetitive counting and overestimation.

Proportion of streams with peatlands influence

$P_{Stream(i)}$ refers to the proportion of streams with peat influence before draining into peat-fed water supply reservoirs. $P_{Stream(i)}$ was calculated by the amount of flow accumulation at peatland outlets divided by the value of flow accumulation of the reservoir outlets.

Volume of streams with peatlands influence in PPI hotspots

Determining PPI hotspot catchments

In this study, the Jenks optimisation method was used to classify the level of PPI and therefore to determine PPI hotspots. Jenks optimisation allows continuous variables to be binned into meaningful, non-arbitrary categories. Jenks optimisation is a data clustering method designed to determine the best arrangement of values into different classes, seeking to reduce the variance within classes and maximize the difference between classes[27], and is widely used in geographic information science[55-57]. The Jenks optimisation method is also known as the goodness of variance fit (GVF), and the optimization is achieved when the quantity GVF is maximized: (1) Calculate the sum of squared deviations between classes (SDBC); (2)

Calculate the sum of squared deviations from the array mean (SDAM); (3) Subtract the SDBC from the SDAM (SDAM-SDBC). This output equals the sum of the squared deviations from the class means (SDCM). The method first specifies an arbitrary grouping of numeric data. SDAM is constant and does not change unless data changes. The mean of each class is computed, and the SDCM is calculated. Observations are then moved from one class to another in an effort to reduce the sum of SDCM and therefore increase the GVF statistic. This process continues until the GVF value can no longer be increased.

The threshold of the highest two PPI categories is 106 persons km^{-2} in the catchments by using the Jenks optimisation classification method. There are eight catchments with a PPI value greater than or equal to 106 persons km^{-2} while the PPI values of all other catchments were less than 100 persons km^{-2}. Therefore, in this study, the top eight catchments with a PPI value no less than 106 persons km^{-2} were identified as PPI hotspots. The processing steps to estimate the volume of potable water provided from peatlands in each PPI hotspot catchment were as described below.

Determining potable water sources in PPI hotspots

There is no available database that shows the water supply system abstraction points and pathways for redirected potable water within the PPI hotspot catchments. Therefore, for PPI hotspots, we obtained as much data as possible from currently available data in the public domain (see Supplementary Text).

Determining volume of peat-fed stream abstraction

We: (1) identified the peatlands which have interacted with streams before draining into water sources by combining the distribution of potable water sources, PEATMAP and river network systems; (2) identified the outlets of potable water supply peatlands and peat-fed water sources and calculated the proportion of stream flows which have interacted with peatlands before draining into peat-fed rivers based on the flow accumulation dataset; (3) estimated the volume of annual water directly supplied from potable water supply peatlands in the PPI hotspots (directly-sourced peat-fed potable water) by multiplying the volume of annual water supplied from peat-fed water supply rivers (mixed-source peat-fed potable water) and the proportion of stream flows which have interacted with peatlands before draining into peat-fed water rivers.

Determine upland peatlands in high PPI catchments

There is no standard definition of upland peatlands, but we applied the term to peatlands more than 300 m above sea level (ASL) which approximates to definitions commonly used in the UK[58,59], since most of the potable water supply peatlands are located in the UK.

The threshold of the highest three PPI categories for catchments is no less than 36 persons km^{-2} using the Jenks optimisation classification method. There are 46 catchments with a PPI value of no less than 36 persons km^{-2}. Therefore, in this study, the top 46 catchments with a PPI value no less than 36 persons km^{-2} were chosen as the highest PPI catchments (PPI hotspots are the top eight catchments with a PPI value no less than 106 persons km^{-2}). Upland peatlands in high PPI catchments were isolated using elevation values derived from the 15 arc-second DEM provided by HydroSHEDS by ArcMap 10.4.

Determine land-use status of potable water supply peatlands

The Ecosystem-Land Use System[33] is a 5 arc minutes (9.25 km at the Equator) resolution global land use systems for assessing land degradation, which has been recently developed by FAO in close collaboration with the World Overview of Conservation Approaches and Technologies. This Land Use System contains 36 classes based on a combination of land cover, agricultural activities (high medium low) and management (irrigation/protected/no use). Here we overlapped global water-supply peatlands with Ecosystem-Land Use System to determine the land use of these peatlands. We removed from the analysis those land-use types which were not found on water-supply peatlands and then combined some similar land-use categories to aid analysis (Supplementary Table 2).

Data availability

The main data supporting the findings of this study are available within the article and its Supplementary Information files. These data and any associated data is available from University of Leeds open access data repository.

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Competing financial interests

The authors declare no competing financial interests.